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Piloted Evaluation of an Integrated Methodology for Propulsion and Airframe Control Design

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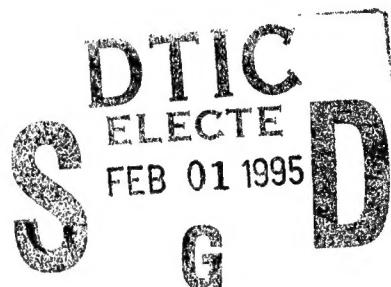
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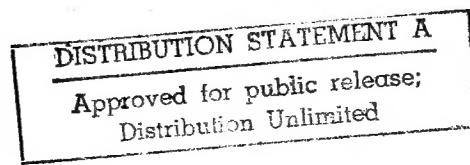
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ABSTRACT

An integrated methodology for propulsion and airframe control has been developed and evaluated for a Short Take-Off Vertical Landing (STOVL) aircraft using a fixed base flight simulator at NASA Lewis Research Center. For this evaluation the flight simulator is configured for transition flight using a STOVL aircraft model, a full nonlinear turbofan engine model, simulated cockpit and displays, and pilot effectors. The paper provides a brief description of the simulation models, the flight simulation environment, the displays and symbology, the integrated control design, and the piloted tasks used for control design evaluation. In the simulation, the pilots successfully completed typical transition phase tasks such as combined constant deceleration with flight path tracking, and constant acceleration wave-off maneuvers. The pilot comments of the integrated system performance and the display symbology are discussed and analyzed to identify potential areas of improvement.

INTRODUCTION

The Advanced Control Technology Branch at NASA Lewis is conducting research in the area of integrated flight and propulsion control design specifically for a STOVL aircraft. This methodology is referred to as IMPAC -- Integrated Methodology for Propulsion and Airframe Control. The two significant features of the IMPAC methodology are centralized control design and partitioning. The methodology considers the airframe and propulsion systems as one integrated system. A centralized controller is designed

from this integrated system. The methodology then partitions the centralized controller into decentralized subsystem controllers. Additional information on this methodology and its application are found in reference [1].

The purpose of this paper is to describe the evaluation of the IMPAC methodology using the NASA Lewis fixed based flight simulator. This evaluation demonstrates the effectiveness of both the flight simulation facility and the IMPAC design methodology for piloted evaluation of an integrated flight and propulsion control design. The paper includes a brief description of the simulation environment, the cockpit configuration and displays, the ghost guidance description, vehicle models and control design descriptions, control design implementation and modifications, and the flight scenarios and profiles used for the piloted testing in the simulator. Pilot comments and conclusions about the controllability, performance, and workload associated with the control design and recommendations for enhancements are given.

DESCRIPTION OF FACILITY

The facility used for this control evaluation, as shown in Figure 1, is the NASA Lewis fixed based flight simulator. It consists of an image generation system, a UNIX development station, a mockup cockpit, a real-time simulation computer, and a control computer system. The image generation system simulates the Heads Up Display (HUD) and the out-

the-window scenery using three video channels to provide a 150 degree field of view. The cockpit provides pilot effectors to produce commands for the engine and airframe. The simulation computer executes the engine and airframe physics models in real time. Finally, the control system computer executes the integrated control design algorithms. A complete description of this simulation facility is given in reference [2].

Cockpit Configuration

Figure 2 outlines the cockpit configuration for the STOVL aircraft piloted simulation based on the STOVL task tailored control mode implementation study of reference [3]. From this study the sidestick controller acts as a rate command and attitude hold system for pitch and roll during transition flight. The throttle commands vertical flightpath angle and the rudder pedals command sideslip. An additional cockpit effector, the thumbwheel, is located on the throttle. The thumbwheel commands acceleration and deceleration along the flightpath. Also from Figure 2, two switches are shown on the sidestick controller. The mode switch controls the on/off logic of the ghost guidance symbol (which is discussed in a later section), and the trigger switch resets the simulation. Additional information on the establishment of cockpit effector gradients and deadbands for this simulation can be found in reference [2].

Displays

The HUD symbology is shown in Figure 3. The HUD is based on pilot vehicle research by Merrick, et al. [4] In order to mimic this symbology without the use of an actual glass HUD, the symbology is generated and updated by the image generation computer and overlayed on the scenery on the projection screen.

The displays and scenery are modified to reflect an integrated engine and airframe control task, typical of a STOVL aircraft. The HUD symbology includes a moving pitch ladder, heading scale, and flight path marker to provide information on aircraft attitude with respect to the aircraft reference symbol. Additionally, aircraft parameters such as altitude, airspeed, forward acceleration, and vertical acceleration rates are displayed on either side of the HUD. Two moving carets on either side of the HUD are added to the symbology to indicate thumbwheel position and throttle position. Since there is no detent

for the throttle or thumbwheel, these caret indicators allow the pilots to zero their acceleration or flightpath commands without looking down at their hands. Finally, the flight path angle, angle of attack, and sideslip angle are numerically displayed on the HUD. When the angle of attack (AOA) or airspeed limits are hit during the simulation, the AOA symbol or airspeed symbol illuminates red to signal a limitation. This symbology was implemented after several iterations of pilot comments and simulations prior to the final evaluation.

Ghost Guidance Logic

The pilots are also provided with vertical, lateral, and roll guidance logic in the form of a "ghost" guidance symbol included in the HUD symbology shown in Figure 3. This pilot activated symbol provides vertical and lateral guidance during an approach to the runway. The logic to implement this symbol is based upon the work performed by Merrick et. al. described in reference [4].

The ghost guidance symbol is a white aircraft-shaped symbol which moves vertically, horizontally, and rolls within the HUD. It is programmed to lead the pilot along a reference vertical flight path of -3.0 degrees to the runway and then level off over the center of the runway at a reference hover altitude of 82 feet. The pilot tracks the ghost symbol by overlaying it with the flight path symbol. The lead distance, roll attitude, elevation angle (longitudinal), and azimuth angle (lateral), of the ghost symbol with respect to the actual aircraft is dependent upon several factors including the actual aircraft present position, orientation, and velocity as well as the position and attitude of the aircraft at the time of guidance logic activation. If the pilot is performing a vertical tracking task (i.e. starting with a heading parallel and aligned with the runway), his workload will consist of adjusting the longitudinal flight path to overlay the guidance symbol. For a combined tracking task (i.e. laterally offset from the runway), the pilot must make both longitudinal and lateral adjustments in flight path to track the ghost which flies a predefined curved path to the runway. The pilot activates the guidance logic by pressing a toggle switch located on the sidestick controller. Pressing the same switch a second time will de-activate the logic and remove the ghost symbol from the HUD.

VEHICLE DESCRIPTION AND MODELS

For the evaluation of this integrated control design, a piecewise linear airframe model was created to simulate the dynamic operation of an ejector-configured conceptual STOVL aircraft (E-7D) over the transition flight envelope. This model serves two purposes: to evaluate the airframe control design in non-real-time, and to simulate the real-time aircraft model during control evaluation. The simulation methodology is based on a piecewise linear state variable technique described in reference [5]. Within this process, the airframe model uses state variables and matrix formulations to represent the airframe at 16 different operating points consisting of flight paths of -6, -3, 0, and 3 degrees, and velocities of 60, 80, 100, and 120 knots. An interpolation scheme is used to update and maintain an accurate model as the aircraft transitions between the operating points in the flight envelope.

The piecewise linear airframe model is integrated with a multi-nozzle turbofan engine model. The aircraft model is configured with the following control effectors: left and right elevons, rudder, ejectors to provide propulsive lift during low speeds, a 2-dimensional convergent/divergent aft nozzle, a vectoring ventral nozzle for pitch control and lift augmentation during transition, and a Reaction Control System (RCS) for pitch, roll, and yaw control. The engine compressor bleed flow is used for RCS thrusters and the mixed engine flow is used as the primary ejector flow. Detailed ducting diagrams of the engine and discussion of the ejector STOVL concept are available in reference [6].

For this evaluation, the integrated engine and airframe model for the STOVL aircraft was limited to the transition flight envelope. Based on the transition envelope, the velocity was limited between 65 kt and 120 kt and the acceleration was limited between ± 0.1 Gs. Lateral roll angle was limited to ± 20 degrees and directional angle was limited to ± 10 degrees. Angle of attack limits were set at 4 and 14 degrees, and flightpath angle limits were set at -6 and 4 degrees for velocities above 80 kt.

CONTROL DESIGN IMPLEMENTATION

Figure 4 is a block diagram of the full integrated flight and propulsion control (IFPC) system. The main elements of the IFPC system are briefly described below and are further detailed in reference

[1]. The airframe control subsystem consists of the following four main sections: the pilot gradients and command limiting; the lateral controller and limit logic blocks; the longitudinal measurement blending, controller, and limit logic blocks; and the airframe trim schedules. The pilot gradient and command limiting block provides rate and range limits, and it scales the pilot effectors to appropriately sized commands. The resulting commands are then passed to both the lateral and longitudinal controllers. The lateral control system maintains closed-loop control of roll rate, yaw rate and the sideslip angle using the ailerons, rudder, and roll and yaw RCS. The longitudinal control system maintains closed-loop control of pitch angle and rate, forward velocity and acceleration, and the flight path angle using the elevons, aft nozzle angle, ventral nozzle angle, pitch RCS, and thrust from the aft and ventral nozzles and the ejectors. The trim schedules provide the nominal steady state operating point information for all of the actuators, including the nominal thrust values. The limit protection scheme bounds the hard actuator limits for both the lateral and longitudinal controllers and provides limit information back to the nominal controllers to prevent integrator windup and to maintain closed-loop stability while trying to maintain closed-loop performance.

The engine control subsystem acts on thrust commands from the longitudinal control system. The airframe trim schedules also provide thrust trim commands and gain scheduling variables to the engine subcontroller. The engine subcontroller consists of the following four main sections: the fan speed schedule, the nominal engine controller, the safety and actuator limit logic, and the thrust estimator. The fan speed is scheduled as a function of the total commanded thrust. The nominal engine controller maintains closed-loop control over fan speed and the three estimated engine thrusts (aft and ventral nozzles and ejectors). While fan speed is measured directly, a measure of actual engine thrust is not available, so a nonlinear static model of the engine provides estimates of the engine thrusts given the available engine information. The engine achieves the closed-loop control by manipulating the fuel flow, the ejector butterfly valve position, and the aft and ventral nozzle areas. The engine limit logic contains actuator rate and range bounds and operational limits for the engine, consisting of the accel/decel fuel flow limits, the fan stall margin, minimum burner pressure, and fan rotor overspeed. Limit information is fed back to the nominal control system to maintain stability during

limit conditions. A second version of the thrust estimator is used to calculate thrust bounds based on the engine accel/decel schedule. These thrust bounds are fed back to the longitudinal controller actuator limit block to provide thrust command limits for the longitudinal controller.

Control Law Modifications

Initial piloted evaluations of the IFPC design in the real-time simulation environment uncovered some problems which had not been apparent in the non-real-time evaluation. One of the problems was a high frequency pitch oscillation during the decelerating maneuver. Shown in Figure 5 is the pitch attitude (θ) response of the aircraft for a simulated pilot command of simultaneous flight path change of -3 degrees and deceleration command of 1.3 ft/s^2 (0.04 Gs). The solid line in Figure 5 corresponds to the nominal IFPC design and shows the high frequency pitch oscillation. An analysis of the timing diagram for the simulation facility in Reference [2] indicated that there is significant time delay in the communication between the simulation computer and the control computer. The effect of this time delay on the system performance was modelled in the non-real-time simulation by incorporating a time delay of 20 ms both at the integrated airframe/engine plant inputs and at the outputs. With this addition of the time delay, the pitch oscillation could be duplicated in the non-real-time simulation, indicating that the time delay was the cause of the oscillation. Investigating the linear, integrated, closed-loop system at 100 Knots showed the existence of a high frequency, lightly-damped pitch mode. With the phase loss due to the time delay in the real-time simulation environment, the damping of this mode is further decreased resulting in the observed oscillatory behavior.

To improve the damping of the high-frequency pitch mode, the IFPC design was modified to include an additional constant gain feedback loop from the pitch rate error (eq) to the elevator (δe), i.e. $\Delta\delta e_c = Keq \bullet eq$. Root locus analysis techniques were used to determine that a value of $Keq = -0.3 \text{ deg/deg} \bullet s^{-1}$ provides the most damping for the high frequency pitch mode without having any significant effect on the rest of the closed-loop pole locations. The real-time system pitch attitude response to the simulated pilot command with this modification is also shown in Figure 5. In comparison to the nominal system, the modified system shows a well damped pitch response.

Another problem discovered during initial piloted simulations was a low frequency oscillation in the flight path (γ) response to flight path commands (γ_c). This oscillation was severe around the 100 Knots flight condition, and the pilots commented that tight tracking of the vertical flightpath would result in pilot-induced oscillations. Shown in Figure 6(a) is the real-time system response to a simulated pilot command in flight path for the 100 Knot airspeed flight condition. This problem could not be duplicated in the non-real-time simulation even after the inclusion of the time delay. It was conjectured that the differences between the actual and estimated thrusts (estimated thrust is used in the control feedback while actual thrust is used as input to the airframe simulation), in combination with the time delay in the thrust feedback result in excitation of a low-frequency, lightly-damped vertical mode. The vertical damping of the closed-loop IFPC system was improved by adding a feedback loop from the flight path error ($ey = \gamma_c - \gamma$) to the ejector thrust (FGE), i.e. $\Delta FGE_c = Key \bullet ey$. A value of $Key = 200 \text{ lbs/deg}$ was selected for the 100 Knots condition by varying the gain in the real-time simulation and studying its effect on the response to flight path commands. The gain Key was varied linearly with airspeed (V) for $80 \leq V \leq 120 \text{ Knots}$, and $Key = 0$ outside this range. As shown in Figure 6(b), this modification results in an improved response to pilot commands in flight path command.

Other modifications to the IFPC, based on initial piloted evaluations, consisted of adding heading-hold control logic and transient in-phase coupling in the pilot commands. The nominal IFPC design provides a roll rate command/attitude hold response with automatic turn coordination. When the pilot commands zero roll attitude (level flight condition), residual errors in the bank angle response result in heading deviation build-up because of the automatic turn coordination feature. Extensive logic was added to override the turn coordination feature for small ($< 0.1 \text{ deg}$) roll attitude commands, and an additional feedback loop from heading angle error to the yaw RCS area actuator was provided to hold heading.

The IFPC system was designed to provide decoupled tracking of pilot commands. However, some coupling in the transient response is unavoidable due to the limitations on control power and control rate. The nominal IFPC system tended to have out-of-phase coupling between the various responses, e.g. flight path up command results in initial pitch down response. The pilots found such out-of-phase response

to be disturbing and it distracted them from performing the desired tasks. Small in-phase transient command coupling was added in the command shaping and prefilter block of the IFPC design to reduce the effect of the out-of-phase response of the feedback loop in the nominal IFPC design.

EVALUATION TASKS AND PROCEDURES

In order to evaluate the performance of the integrated control design, a piloted simulation was performed on the fixed base flight simulator. The major objectives of the piloted evaluation were to assess controllability, performance, and workload during a series of four flight scenarios. The four scenarios included a vertical tracking task, a combined tracking task, an abort sequence, and a general maneuverability sequence.

For both of the tracking tasks the pilot's objective was to maintain precise control of the flightpath symbol by overlaying it on the ghost guidance symbol. The scenario would begin on a 0 degree flightpath at level altitude with the ghost aircraft. The ghost, however, began on a -3 degree approach to the runway with a 10 second lead distance. In this fashion, the pilot would have to acquire a -3 degree flightpath and match that flightpath for 10 seconds to track the guidance symbol. The ghost symbol would "fly" the optimal trajectory to a simulated, low speed landing 82 feet above the runway, and the pilot would "track" the ghost through various starting conditions and gust conditions to a simulated landing. The four scenarios for this evaluation are described as follows:

(1) Vertical tracking task: The objective of this task is to perform a moderate tracking scenario and a tight tracking scenario. The moderate tracking task is less difficult to perform because the pilot begins acquisition of the ghost symbol at a distance further from the runway, thus allowing for more time to acquire the flightpath. The moderate tracking task begins at 760 ft altitude with an 18000 ft approach distance. The pilot maintains precise flightpath control and a constant deceleration of 0.04 Gs from 120 kt to 70 kt and levels out at 82 ft altitude, holding 70 knots. The tight tracking task begins at 470 ft altitude with a 12000 ft approach, and the pilot maintains a 0.06 G deceleration from 120 kt to 70 kt. Then the pilot levels out at 82 ft altitude and holds 70 knots. The heading of the aircraft is aligned with the runway.

The scenario is performed with no gust and moderate gust. The pilot then assesses his ability to maintain constant decel. He also assesses pitch and flightpath decoupling and rates the effect of gust on workload.

(2) Combined tracking task: The objective of this tracking task is the same as the vertical tracking task, except now the scenario is initiated with the aircraft laterally offset from the runway. The pilot maintains a constant 0.04 G deceleration from 120 kt to 70 kt and levels out at 82 ft altitude. The scenario begins at 760 ft altitude and 18000 ft approach. A lateral offset of 3 degrees is used for the moderate tracking task and 6 degrees is used for the tight tracking task. The scenario is performed with no gust and moderate gust. The pilot assesses the coupling between the axes, and tests the independent control of lateral and vertical flight path.

(3) Abort approach to runway and go around: This scenario begins as in task 1, however, as the pilot approaches the runway hover point, he aborts the approach and performs one of three maneuvers: a level, constant speed turn; a climbing, constant speed turn; or a climbing, accelerating turn. After performing a 360 degree turn, the pilot reacquires the runway and recaptures the ghost guidance symbol. The objectives for this task are to evaluate the control capability to perform the task, and to assess the decoupling of roll and flightpath.

(4) General maneuverability: This final scenario is initiated at 80 kt. and 1000 ft altitude. The pilot performs three tasks: a large flight path change from -6 to +4 degrees in range, a large pitch maneuver with a change of ± 10 degrees from the nominal +7 degrees (bounded by the angle of attack limits of +14 and -4 degrees), and a large accel/decel command of ± 0.08 Gs. The objectives of this task are to assess the controllability and predictability of the aircraft response during excessive excursions from the nominal flight.

Two pilots, one with V/STOL and powered-lift aircraft experience, and the other with extensive fighter experience, performed these evaluations. A discussion follows of their comments and ratings on workload and performance of the control design.

PILOT COMMENTS AND RESULTS

For the first task, vertical tracking, figure 7 gives a time history of deceleration, velocity,

flightpath, and pitch commands. These responses shown are for the non-STOVL pilot. As shown in figure 7, the controller tightly tracked acceleration and velocity commands. The flightpath command is also tracked well, although there is some delay in response due to control communication delays. From the flightpath time history it can be seen that the pilot continually made corrections to the flightpath, thus, this non-STOVL pilot did not acquire the ghost symbol and track it for at least 10 seconds (which is the amount of lead distance between the ghost and the actual aircraft). Additionally, as shown in figure 7, there exists a significant initial pitch deviation due to deceleration command. From the pilot comments this pitch excursion would be bothersome in motion base simulation or instrument only. Gust, however, had no effect on performance or workload for this task.

For the second task, combined tracking, the time histories appear in figure 8. Again the velocity is tracked very well. Both the bank angle and the heading commands are tightly tracked. Sideslip response is virtually zero, which indicates the automatic turn coordination capability. The pilots noted good performance in independent control of vertical and lateral flightpath. However, control sensitivity differences caused lateral overshoot of flight path at low speed. This was due to the flightpath logic and gain sensitivities were not optimized for low speed operation. Again, gust had no significant effect on performance or workload.

For the third task, abort and go around, the pilots expressed good capability of the control to perform both constant speed and constant acceleration wave-offs. The pilots were able to simultaneously command acceleration, climb, and roll without loss in performance. There did exist noticeable coupling in flight path response to acceleration command. However, if the pilot did not stay in the loop to correct flightpath, then these oscillations damped out. Although the pilots still found pitch deviations due to acceleration command to be objectionable, they were able to perform all the abort sequences without loss of stability or performance.

In the final task, general maneuverability, the pilots performed the large maneuvering tasks. During the command of large flight path changes (-6 to +4 degrees), the pilots commented on good velocity hold. Some small amplitude, low frequency pitch oscillations occurred during this maneuver, but, they did not increase workload. While commanding large

pitch attitude changes (4 to 14 degrees), the pilots were successful and commented on good velocity hold. Small deviations in flightpath did occur during this maneuver. This did not increase workload, but, the large settling time for flightpath could be a problem for combined pitch and flightpath changes.

The only problem during the general maneuverability scenario arose during the command of large acceleration/deceleration commands (± 0.08 Gs). The pilots found the excessive pitch deviations to be unsatisfactory. These pitch deviations were due to actuator saturation limits in the engine.

Based on the piloted evaluation, there were two major deficiencies in the IFPC design. The first deficiency was the larger than expected coupling in the pitch attitude response for acceleration and flightpath commands. The IFPC design was based on the idea that it is important to provide the pilot with good flightpath and velocity command tracking capability for successful accomplishment of the typical STOVL transition phase tasks. Not enough emphasis was paid to tightly maintaining the nominal pitch attitude, as it was felt that the pilots could correct for any uncommanded pitch deviations using the independent pitch control. The pilot comments, however, indicate that greater attention needs to be paid to the pitch axis in the IFPC design.

The second deficiency in the IFPC design was the poor response of the aircraft for large deceleration commands. Multiple actuator limits were encountered for these commands and resulted in severe deviations in the pitch attitude. In the IFPC design, the integrator wind-up protection gains were designed to accommodate a single actuator saturation at a time. Furthermore, the integrator wind-up protection gains were optimized to maintain commanded flightpath and velocity response. The pilot comments, however, indicate the need to accommodate multiple actuator saturations with a priority on minimizing uncommanded excursions in the pitch attitude.

CONCLUSIONS AND RECOMMENDATIONS

An integrated flight and propulsion control design was developed and evaluated on the fixed base flight simulator at NASA Lewis. The integrated control system, which was designed for a STOVL aircraft, was evaluated for the transition phase of flight by two pilots. One of the pilots had extensive V/STOL experience and the other pilot had considerable fighter

background. After performing the evaluation tasks for vertical tracking, combined tracking, abort and go around, and general maneuverability, the pilots responded with favorable comments about performance and workload for all the tasks.

The pilot comments revealed good vertical flightpath tracking with excellent decoupling from velocity and lateral response. Also, the comments reflected a good capability to maintain steady deceleration while tracking the ghost symbol to a simulated landing. The pilots could successfully perform abort sequences and large maneuverability changes without loss of control predictability or excessive workload. There did exist, however, uncommanded pitch deviations due to coupling with flightpath and acceleration commands. These pitch deviations could become objectionable in moving base simulation and indicate a need for better pitch regulation in the integrated control design. Some pitch deviations occurred due to coupling of pitch and deceleration commands caused by actuator saturations from the engine control. Overall, the integrated control design gave successful performance in its first piloted simulation of the STOVL maneuvers, and this study assisted in revealing improvements for an integrated control redesign.

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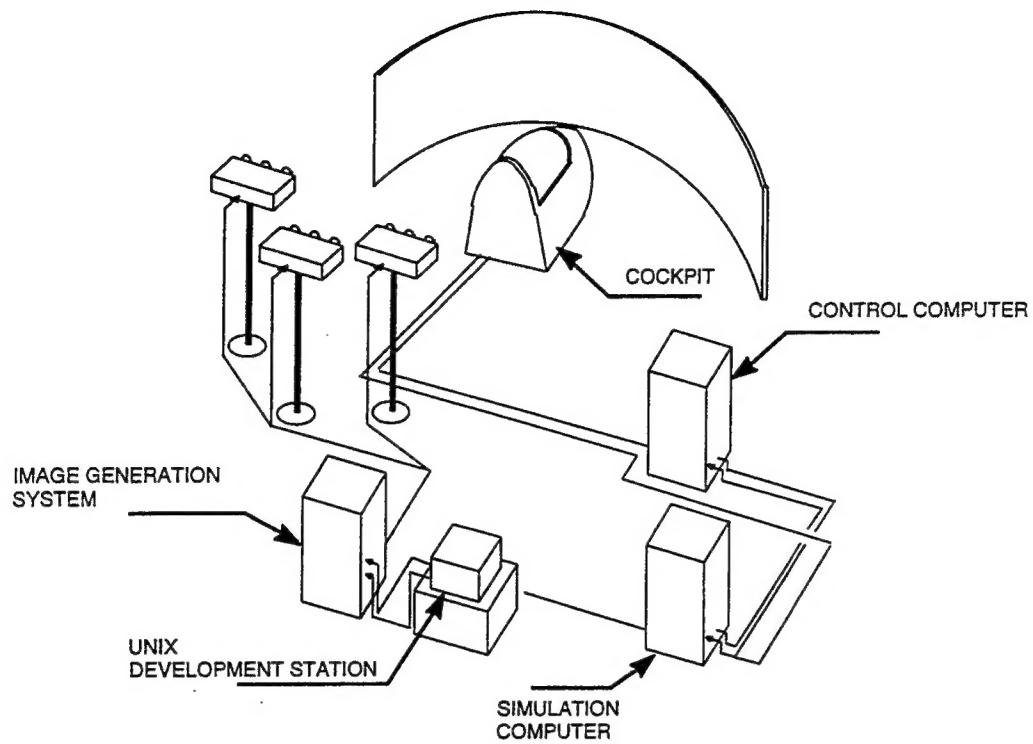


Figure 1. Flight Simulator Facility

pilot command \ control inceptor	Throttle	Thumb Wheel	Longitudinal Stick	Lateral Stick	Rudder Pedals
accel/decel		X			
flightpath	X				
roll/rollrate				X	
pitch/pitchrate			X		
sideslip					X

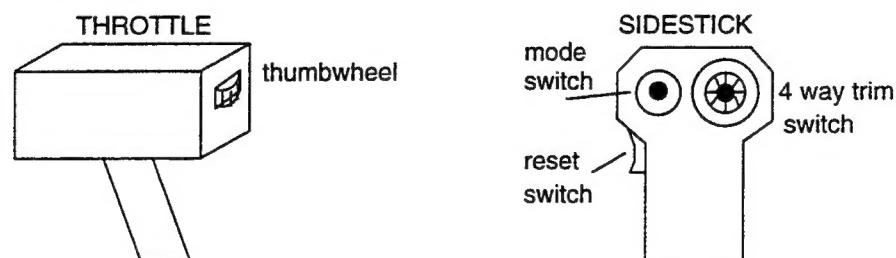


Figure 2. Cockpit Effector Configuration

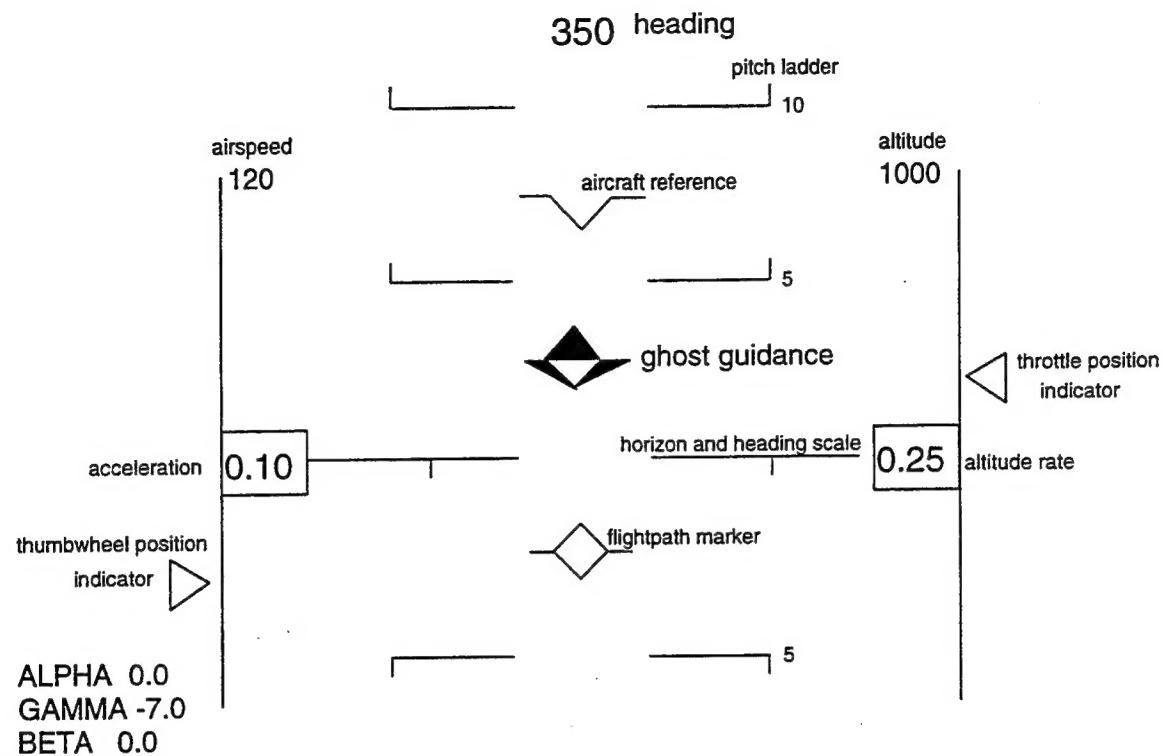


Figure 3. Heads Up Display Symbology for Transition Flight

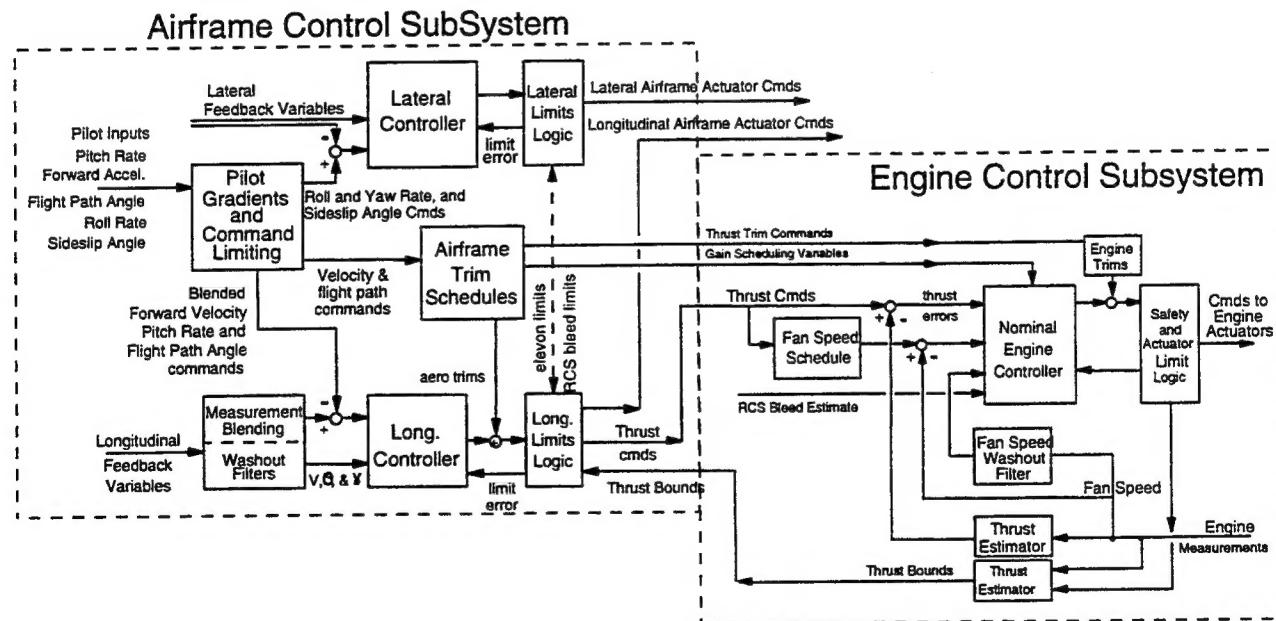


Figure 4. Integrated Controller

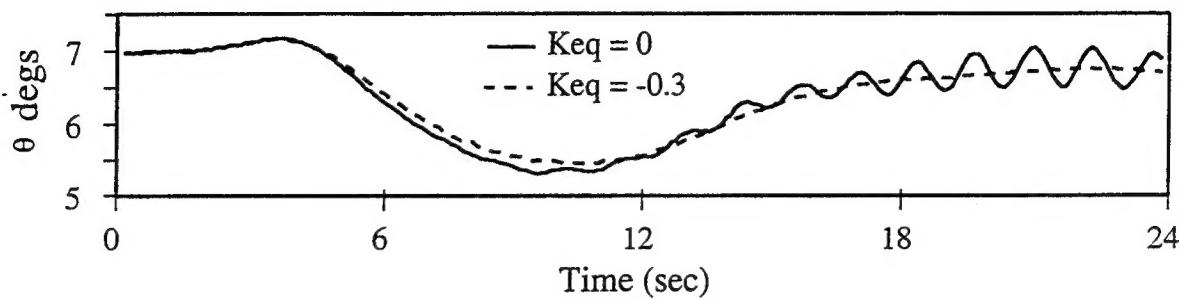


Figure 5. Realtime System Pitch Response to Simultaneous Flight Path and Deceleration Command

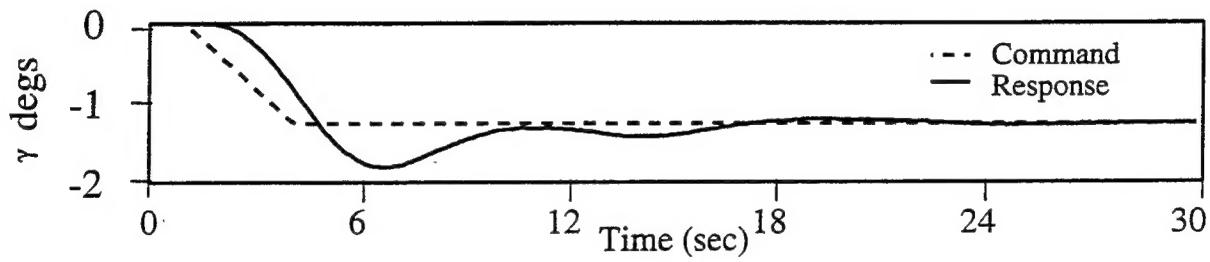


Figure 6(a) Nominal IFPC System Flight Path Response to Flight Path Command

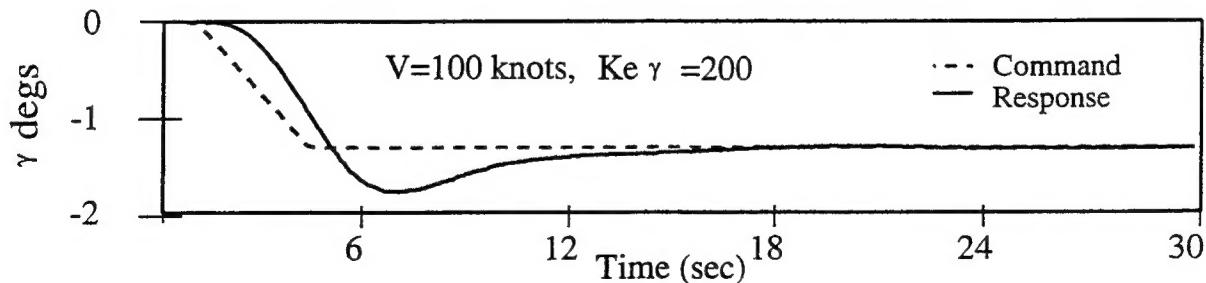


Figure 6(b) Modified IFPC System with Flight Path Error Feedback to Ejector Thrust Command

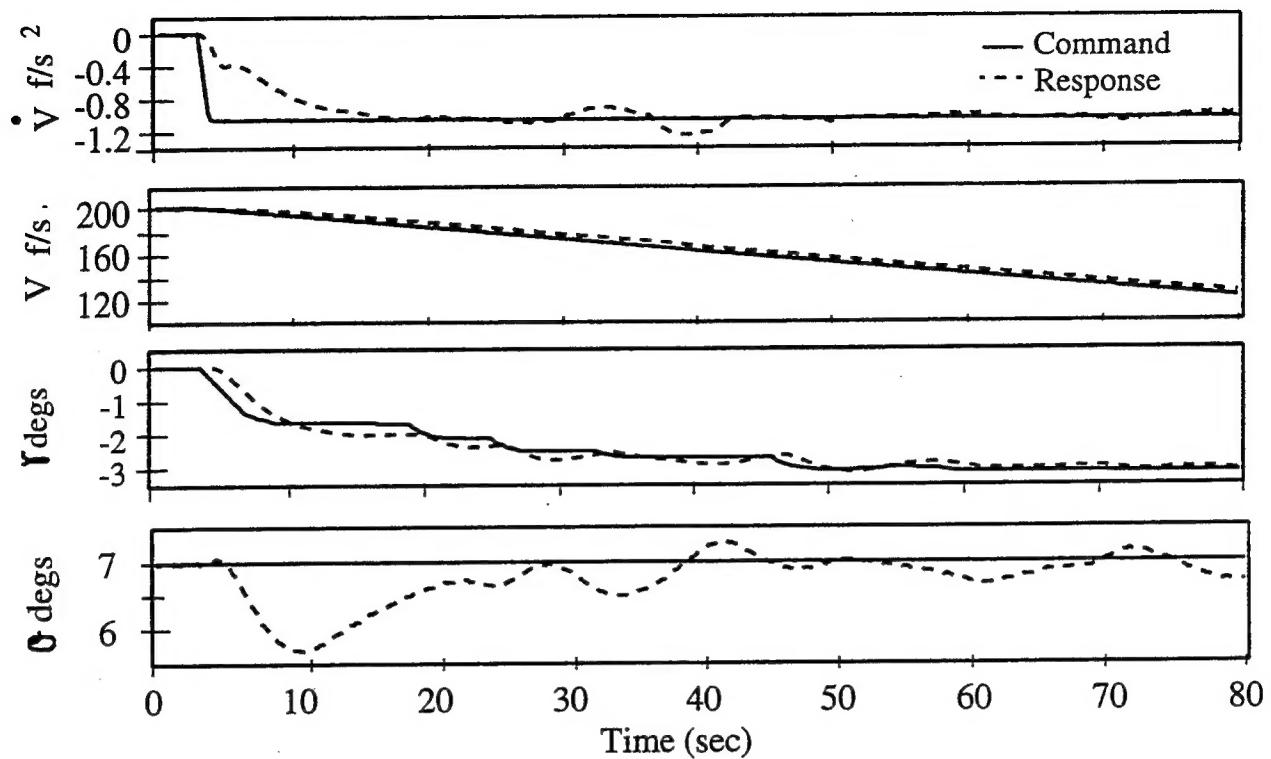


Figure 7. Time Histories for Vertical Tracking Task

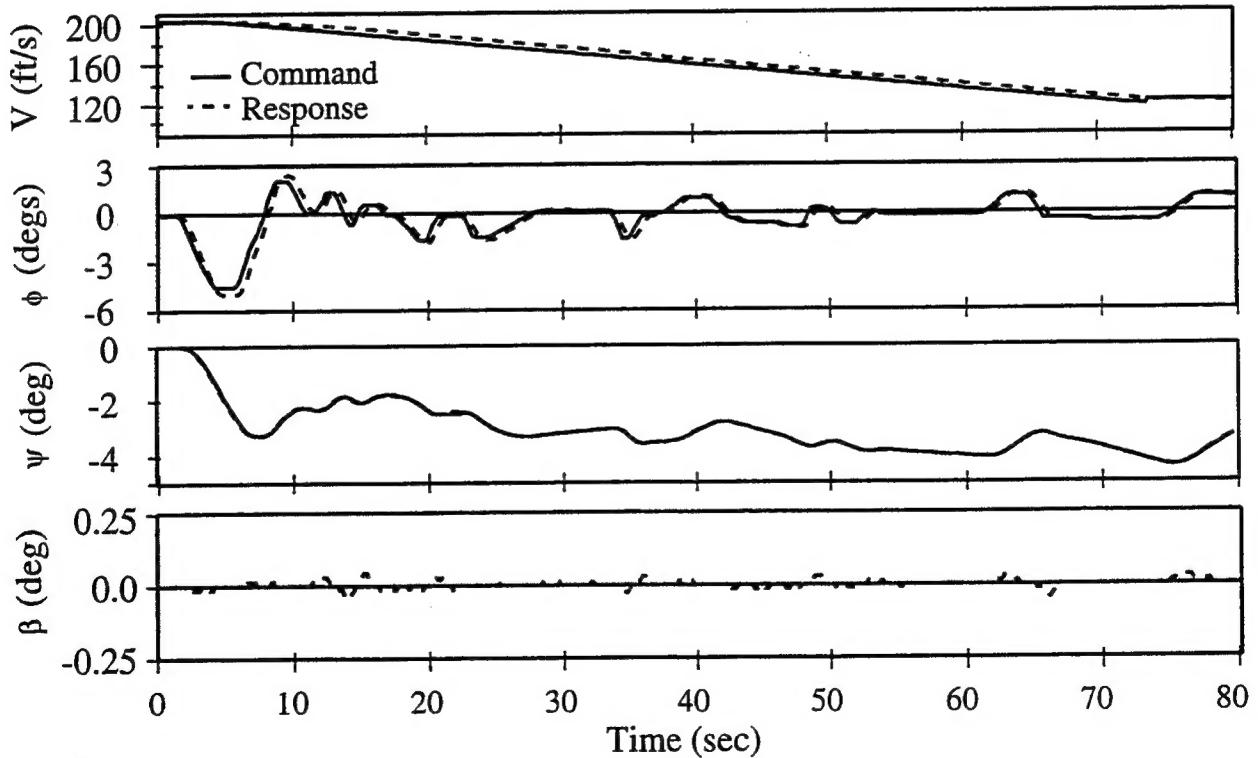


Figure 8. Time Histories for Combined Tracking Task

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An integrated methodology for propulsion and airframe control has been developed and evaluated for a Short Take-Off Vertical Landing (STOVL) aircraft using a fixed base flight simulator at NASA Lewis Research Center. For this evaluation the flight simulator is configured for transition flight using a STOVL aircraft model, a full nonlinear turbofan engine model, simulated cockpit and displays, and pilot effectors. The paper provides a brief description of the simulation models, the flight simulation environment, the displays and symbology, the integrated control design, and the piloted tasks used for control design evaluation. In the simulation, the pilots successfully completed typical transition phase tasks such as combined constant deceleration with flight path tracking, and constant acceleration wave-off maneuvers. The pilot comments of the integrated system performance and the display symbology are discussed and analyzed to identify potential areas of improvement.							
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